Snowmass2021 - Letter of Interest

Low Background kTon-Scale Liquid Argon Time Projection Chambers

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NF Topical Groups:

■ (NF1) Neutrino oscillations
■ (NF3) Beyond the Standard Model
■ (NF4) Neutrinos from natural sources
■ (NF5) Neutrino properties
■ (NF6) Neutrino cross sections
■ (TF11) Theory of neutrino physics
■ (NF9) Artificial neutrino sources
■ (NF10) Neutrino detectors

Other Topical Groups:

■ (CF1) Dark Matter: Particle-like
■ (IF8) Noble Elements
■ (UF01) Underground Facilities for Neutrinos
■ (UF02) Underground Facilities for Cosmic Frontier
■ (UF03) Underground Detectors

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Abstract: With controls over radiopurity and some modifications to a detector similar to the DUNE Far Detector design we find that it is possible to increase sensitivity to low energy physics in a fourth 10 kt module. In particular, sensitivity to supernova and solar neutrinos can be enhanced with improved MeV-scale reach. Furthermore, sensitivity to Weakly-Interacting Massive Particle (WIMP) Dark Matter (DM) becomes competitive with the planned world program in such a detector.

1 Introduction

A large, low background Liquid Argon Time Projection Chamber in an experiment similar to DUNE could have significant $\mathcal{O}$(MeV) physics reach. Adding such a detector as the DUNE 4th Module of Opportunity[1] could expand the physics scope of this multipurpose detector without distorting the DUNE long-baseline neutrino program. In this Letter we discuss increasing the low energy physics sensitivity by lowering the detector trigger threshold and ordinary event measurement threshold of $\approx$ 10 MeV (of the current DUNE Far Detector designs) to the $\mathcal{O}(1)$ MeV level. This will allow interesting solar neutrino results to be within reach and supernova studies can become greatly expanded.

Furthermore, additional background controls and threshold reduction can expand the reach further into the sub-MeV range, where additional nuclear recoil physics may be achievable. In particular, such a detector could have high mass WIMP sensitivity. We find thresholds of 75-100 keV allow a competitive DM result[2] in a relatively short exposure. Additional low threshold measurements, such as elastic neutrino electron scattering (ES) with solar pp neutrinos and Coherent Elastic Neutrino-Nucleus Scattering (CEvNS) detection could be performed, thus opening a vast field for standard model precision testing.

A guiding principle in this work is to not sacrifice any beam exposure or perturb the main physics charge of the DUNE program, but to expand the physics reach and multipurpose nature of DUNE-like detectors.

2 Physics Aims

The main physics program of DUNE is focused on beam-neutrino physics, measuring nucleon decay, and making supernova (SN) burst neutrino measurements. This module, with reduced radiological backgrounds, most noticeably suppressed ^{39}Ar and neutron background, can expand the supernova reach to lower energy thresholds and further in distance. The introduction of depleted argon by itself increases the reconstruction performance of non-beamline events, improving SN neutrino energy markedly. Further, the densely-instrumented fiducial volume here would allow this module to be a very sensitive SN trigger for the whole detector complex.

Studies[7,5] have shown that the baseline DUNE Single-Phase (SP) 10 kt module can make precision ^{8}B measurements of solar neutrino oscillation parameters. Our proposed new module could make a very clean measurement of as-yet undetected solar *hep* neutrinos. Moreover, a detection threshold down to $\sim 100\,$keV allows for precision ES measurements over the full range of solar neutrino energies, including low energetic pp-neutrinos. ES would also adds pointing capabilities, and measurements of the Weinberg angle at various low energies could be made. Solar neutrino oscillation parameters could be precisely mapped over the full energy range, searching for non-standard neutrino interactions (NSI) inside the sun, which could explain the so-called solar neutrino anomaly[6]. In addition, the proposed reductions in backgrounds could allow measurements of the diffuse supernova background[10] and additional astrophysics (for example directional neutrinos sources).

Ultimately, such low detection thresholds will also allow direct searches for WIMP DM particles with a relatively high radiopurity detector. Reference[2] puts forward a detector design to meet that challenge and concludes that a three year exposure in an inner kton of fiducial volume gives a WIMP sensitivity similar at high masses to DarkSide-20k[9] running for ten years. Further, CEvNS measurements with the GeV beam neutrinos and atmospheric neutrinos could be possible in a $\sim 100\,$keV-threshold detector.

In addition, other physics this detector could investigate include the potential to load with isotopes such as ^{136}Xn to search for neutrinoless double-beta decay (0nubb) that can occur if neutrinos are of Majorana nature. Doping with xenon would have the additional benefit of increased light yield. Other low energy neutrino astrophysics searches could include indirect DM detection.

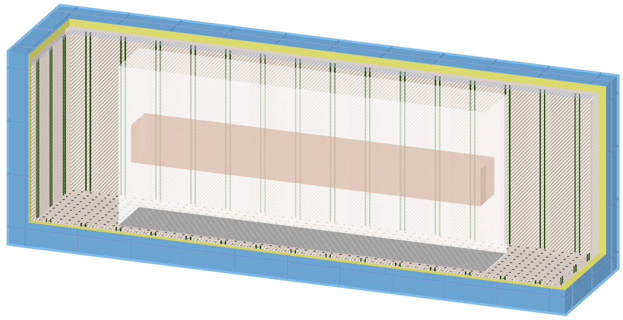

Figure 1: Conceptual drawing of proposed DUNE low background detector module. The fiducial volume is shown by the beige innermost box. The tall white box that surrounds the fiducial volume (extended by a meter on the four sides) makes the detector inner volume. The floor of the detector within this acrylic box is covered in SiPM tiles (black). The field cage is unchanged from the DUNE design, showing the standard resistor divider chains and supports (green) just inside the cryostat. The cryostat is shown in yellow. Outside the cryostat a coarse structure of structural I-beams and 40 cm of water[8] (blue) are shown..

3 Detector Design

The detector module will require the following to operate, and a potential design is shown in Figure 1:

- Dual Phase (DP) - we start from a modified DUNE dual phase detector design, where the large empty mass of bulk argon allows significant fiducialization and self-shielding in the centre of the detector.
- Enhanced Radiopurity - the following radiopurity enhancements will be required:
  - Low radioactivity underground argon - following discussions at[3;4] that indicate underground argon may be obtainable at not-so-large costs, this detector (or at least the volume immediately around the inner fiducial volume) will be filled with argon depleted of ^{39}Ar and ^{42}Ar.
  - Increased detector materials radiopurity requirements - this detector does not require the radiopurity levels achieved by current dark matter detectors, but would require an increase over the baseline DUNE design for the cryostat and I-beams.
  - Improved radon control - significant radon control beyond the baseline DUNE, either through direct radon removal or alpha tagging are required (though not to the levels achieved by the current dark matter experiments).
- Additional Shielding - the spaces between the cryostat support structure (I-beams) are filled with water tanks to reduce external neutron flux. Additional layers of plastic in the argon can be used to reduce this background further.
- Low threshold readout - High signal/noise from, for example, gas-multiplication light readout
- Enhanced photocathode coverage - lower energy thresholds and the potential of pulse shape discrimination for particle identification can be used by improving light detection (particularly the initial scintillation light) by improved quantum efficiency in the photosensors (replacing PMTs with SiPMs), increasing coverage (at least in the central part of the detectors) and through the addition of reflectors.

References

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